Instituto Nacional de Investigación y Tecnología Agraria y Alimentaria (INIA)
http://dx.doi.org/10.5424/fs/2014233-05128

Forest Systems 2014 23(3): 438-447
ISSN: 2171-5068
eISSN: 2171-9845

OPEN ACCESS

Biomass conversion and expansion factors are afected by thinning

Teresa Duque Enes[1,2]* and Teresa Fidalgo Fonseca[3]

[1] Department of Forest Sciences and Landscape Architecture. University of Trás-os-Montes and Alto Douro. 5000-801 Vila Real, Portugal. [2] Centro de Estudos Florestais. Instituto Superior de Agronomia. Universidade de Lisboa. Tapada da Ajuda. 1349-017 Lisboa, Portugal. [3] Department of Forest Sciences and Landscape Architecture. University of Trás-os-Montes and Alto Douro. 5000-081 Vila Real, Portugal

Abstract

Aim of the study: The objective of this paper is to investigate the use of Biomass Conversion and Expansion Factors (*BCEF*s) in maritime pine (*Pinus pinaster* Ait.) stands subjected to thinning.

Area of the study: The study area refers to different ecosystems of maritime pine stands in Northern Portugal.

Material and methods: The study is supported by time data series and cross sectional data collected in permanent plots established in the North of Portugal. An assessment of *BCEF* values for the aboveground compartments and for total was completed for each studied stand. Identification of key variables affecting the value of the *BCEF*s in time and with thinning was conducted using correlation analysis. Predictive models for estimation of the *BCEF*s values in time and after thinning were developed using nonlinear regression analysis.

Research highlights: For periods of undisturbed growth, the results show an allometric relationship between the *BCEF*s, the dominant height and the mean diameter. Management practices such as thinning also influence the factors. Estimates of the ratio change before and after thinning depend on thinning severity and thinning type. The developed models allow estimating the biomass of the stands, for the aboveground compartments and for total, based on information of stand characteristics and of thinning descriptors. These estimates can be used to assess the forest dry wood stocks to be used for pulp, bioenergy or other purposes, as well as the biomass quantification to support the evaluation of the net primary productivity.

Key words: carbon; softwood; thinning; volume; wood energy; maritime pine.

Introduction

Studies of forest biomass are important for the assessment of net primary productivity and carbon storage, quantification of forest residues for commercial purposes (energy and fiber) and ecosystem nutrient recycling. These studies are of great importance for the decision making of forest resource management (Páscoa *et al*., 2004). The use of forest biomass for bioenergy is increasingly recognized in European countries as part of an integrated strategy aimed at mitigating climate change, improving safety renewable energy and forest fire prevention (Viana *et al.*, 2012). A United Nations Framework Convention on Climate Change (UNFCCC) and, in particular, the Kyoto Protocol, also recognize the great importance of forest biomass and carbon and the need to monitor, given its influence on the concentration of the atmospheric CO_2.

Forest biomass can be accessed through two methods: the destructive method, which includes the quantification of weights and/or volumes of individual felled trees, through inventory techniques, and non-destructive methods where the estimation of the biomass (or volume) is supported by regression models, or, for large landscapes scales, by remote sensing technology such as the Laser Imaging Sensor (Parresol, 2002, Picard *et al.*, 2012). In most situations, the first method is reserved for the generation of data to enable the development of the regression models, usually using allometric equations. The general expression is $Y = a\,X^b$, where Y represents the biomass or volume of the stem (or of other compartment), X usually refers to the diameter at 1.30 m, and a and b are the allometric constants. The allometric relationship assumes that the biomass growth is proportional to the growth in diameter. When Y refers to stem volume, the value ob-

* Corresponding author: tenes@portugalmail.com
Received: 10-10-13. Accepted: 11-12-13.

tained can be converted into biomass using an average value of wood density. Further details about biomass estimation based on forest inventories and tree biomass models may be found in the reviews by Pardé (1980), Parresol (1999) and Picard *et al.* (2012). See also Ketterings *et al.* (2001) and Longuetaud *et al.* (2013) for additional relevant information on biomass and volume estimation.

A prompt method for obtaining indirect values of biomass from volume information is based on the Biomass Conversion and Expansion Factors (*BCEF*s). Generically, the *BCEF*s are factors for converting the stem volume into biomass, followed by expansion in quantitative biomass for (an) other compartment (s) of the tree. The factors are calculated as the ratio between the biomass of the compartment under consideration (*e.g.* aboveground; aboveground and roots) and the stem volume (s) of tree (s). This method, originally mentioned by Johnson and Sharpe (1983), has been used by several authors (*e.g.* Brown, 2002; Lehtonen *et al.*, 2004; Somogyi *et al.*, 2006; Faias, 2009; Sanquetta *et al.*, 2011; Castedo Dorado *et al.*, 2012, González-García *et al.*, 2013), for different forest ecosystems.

The use of these factors is extremely useful because most of the forest inventory information relating to the volume of the stand is, in general, easily accessible. The same does not happen with the biomass of the stem and crown, or to individual values of tree variables such as the diameter and height required as input variables for biomass estimation. Due to the simplicity of application, these factors are an interesting method for recovering information expressed in biomass for monitoring changes in biomass and carbon. The use of *BCEFs* is recommended by the guidelines of the Intergovernmental Panel on Climate Change (IPCC, 2006 – Vol 4, Chapter 2, p. 2.12 and following) where information on the quantity of biomass is not available and it is necessary to obtain estimates based on data volume.

In specific studies, prediction models for *BCEF*s have been proposed to better reflect stand characteristics comparatively to the use of a constant and unique (average value) for the species (*e.g.*, Faias, 2009; Sanquetta *et al*., 2011; Castedo Dorado *et al*., 2012; Soares & Tomé, 2012 and González-García *et al*., 2013).

Difficulties with this methodology could arise in managed stands subjected to thinning practices. Both the type and the severity of thinning have influence on forest biomass stocks and on stand characteristics (*e.g.* Baldwin *et al.,* 2000; Luis & Fonseca, 2004; Eriksson, 2006; Ruiz-Peinado *et al.*, 2013), hence, some variation in the factors is expected to occur following a thinning. As the stand grows, the effect of thinning in the stand characteristics will reduce, becoming incorporated implicitly in the state variables of the stands (Hasenauer *et al.*, 1997; Luis & Guerra, 1999 and Fonseca, 2004). Surprisingly, no records of studies regarding thinning influences on the *BCEFs* in managed stands were found in the literature review carried out by the authors.

In Portugal the dominant softwood species for timber and for wood energy is maritime pine, (*Pinus pinaster* Ait.). The species covers 27% of the forest area (885,000 ha) of mainland and is responsible for a volume of 64.1 million m^3. It is also the national softwood species with the highest Low Heating Value (16.9 MJ kg^{-1}), and the second with the highest calorific value expressed in Higher Heating Value (20.2 MJ kg^{-1}), according to Telmo & Lousada (2011). The most common silvicultural model considers rotations of 40 to 50 years with completion of 2-3 thinning with spacings of 5 to 10 years or growth of dominant height of around 2 meters (Oliveira *et al.*, 2000). Shorter rotation length (12 to 15 years) are under discussion as a complementary management option to increase the availability of biomass residues as a fuel for power plants while reducing the risk of forest fires. The growing interest in biomass assessments, not only from the trunk, but also from the crown and roots, makes it interesting to study the expansion and conversion factors for this species.

The objective of this research is to analyze the variation of *BCEFs* in pure stands of maritime pine in time and to investigate whether or not the *BCEFs* values are influenced by the practice of thinning. At this point, we hypothesized that (*i*) the biomass conversion and expansion factor vary with stands characteristics and across time; and (*ii*) thinning could affect the value of the factors.

Material and methods

Study area characteristics

The most representative continuous area of maritime pine in Portugal is located in the North part of the country, namely in the Tâmega Valley (latitude range: 41° 15-41° 52 N; longitude range: 7° 20-8° 00 W). Maritime pine occurs at an altitude of between 100 and 900 m in hilly terrain, with soils derived from granite and schist. The region presents characteristics that are favourable for the species development. The mean annual temperature in the area varies between 13.1°C at the lower altitudinal level (100-400 m) to 9.8°C above 400 m. Mean annual precipitation ranges between 660 mm and 1,400 mm in the lower sites, and between 1,000 mm and 2,900 mm in higher locations (Marques, 1991).

Data collection and stands characteristics

This study uses information from the database on maritime pine semi-permanent plots (Data_Pinaster) created and maintained over the last two decades at the Forest Sciences Department of the University of Trás-os-Montes and Alto Douro. Observations encompass 87 sampled stands in Tâmega's Valley in North Portugal, with 41 plots in stands without evidences of thinning practice in, at least, a 5 year period prior to the measurements and 46 plots with recently thinned, with information prior and after the thinning.

In each stand, circular 0.05-ha plots had been established. Available tree characteristics were diameter outside bark at breast height (*d*, cm) of all living trees, total height (*h*, m) and height to live crown (*hc*, m) for a subset of trees; and mean height of the 100 largest trees per ha for stand dominant height (*hd*, m) evaluation. Diameters were measured to the nearest mm and heights to the nearest dm. Stand age (*t,* years) was evaluated in the dominant trees. Values of site index (*SI*, m), at the index age of 35 years, were estimated using Marques's (1991) model.

For each living tree, stem volume (with bark) and aboveground and aboveground plus root dry weight biomasses were calculated using models by Fonte (2000), and the allometric equations, for the stem, crown and roots components by Lopes (2005), respectively (see Table 1). Briefly, the volume equation was developed with a supporting dataset of 350 felled trees collected along the whole study area in representative stands. The system of allometric equations was based on data from 30 felled trees, collected in the county of Boticas in Tâmega's Valley. The density of the sampled stands was 1062 trees ha^{-1} with a mean age of 35 years (Lopes, 2005; Nunes *et al.*, 2013). Stand volumes with bark (V, $m^3\ ha^{-1}$) were calculated as the sum of the volumes of the individual trees per plot and expanded for the hectare. Aboveground stand biomass (B_{ABVG}, $Mgha^{-1}$) was defined as the sum of stem and crown biomass of the living trees; total stand biomass (B_{Total}, $Mgha^{-1}$) was defined as the sum of aboveground plus root biomass, expanded for the hectare.

Definition and calculation of BCEFs

The general definition of *BCEF* provided by IPCC (2006) is a multiplier with dimension ($Mg\ m^{-3}$) that transform growing stock (m^3) directly into aboveground biomass, or above-ground biomass growth or biomass removals (Mg):

$$B_i = BCEF_i \times V$$

BCEFs can be calculated for each stand (sampling plot), as the ratio of the biomass to the volume:

$$BCEF_i = \frac{B_i}{V}$$

In this paper V refers to the stand volume with bark ($m^3\ ha^{-1}$) and B to the biomass (dry weight, $Mg\ ha^{-1}$) of the i compartment: aboveground (stem and crown)

Table 1. Equations used in the quantification of tree biomass and tree volume of maritime pine

Reference	Structural characteristics	Compartment	Model	R^2	RMSE
Fonte, 2000	n = 350 trees $\bar{d}$ = 26.5 (8.1-50.3) $\bar{h}$ = 16.4 (4.3-28.0)	Stem	$v = 0.0000548\ d^2 + 0.0000345\ d^2h$	0.994	0.0577
Lopes, 2005	n = 30 trees	Stem	$\log b_s = 3.769 + 2.706 \log (d/100)$	0.979	0.0782
	$\bar{d}$ = 21.9 (7.5-35.7)	Crown	$\log b_c = 2.911 + 2.130 \log (d/100)$	0.884	0.1520
	$\bar{h}$ = 13.8 (3.5-22.2)	Roots	$\log b_r = 1.972 + 1.221 \log (d/100)$	0.935	0.0638

n: number of observations. *d:* diameter at breast height (cm). *h:* total height (m). $\bar{d}$ and $\bar{h}$ mean values of diameter and height, respectively; range values inside parenthesis. *v:* stem volume (m^3) *b:* biomass (dry weight, kg) of the *i* compartment, in this case referring to the stem, crown and roots.

and total (stem, crown and roots). Stand volume and biomass were evaluated as described before.

Datasets used in the hypothesis testing

Two distinct datasets were used in this study to properly analyze the factors influencing the biomass conversion and expansion factors.

Time series data without recent thinning

For the time series study, the analysis was restricted to stands not subjected to thinning or not thinned at least in the 5 years period before the measurements were made. Available information refers to 41 permanent plots of undisturbed growth with a total of 105 observations (23 plots with 3 sets of measurements and 18 plots with 2 measurements).

Characterization of the stand variables and of *BCEF*s is shown in Table 2.

Hereafter, the authors will refer to this data as time series dataset. These data comprise maritime pine stands at different stages of development as stated by the age variation, encompassing a wide range of density, volume (V) and biomass (B). The site index values show stands spans by lower quality ($10 \leq SI \leq 14$ m) and higher quality ($18 \leq SI \leq 22$ m), with predominance on the average site-class quality ($14 \leq SI \leq 18$ m). The representation is according to the overall site quality pattern observed in Tâmega's Valley.

Cross sectional data in thinned stands

From the Data_Pinaster set, a total of 46 plots were selected to study the thinning effect. For this subset, information concerning tree and stand level variables was recorded in detail. This allowed characterizing the diameter distribution before and after thinning, and the thinning practices. Characterization of stand variables and of biomass factors before and after thinning is shown in Table 3. The Table 4 summarizes the quantitative description of the thinning interventions made in the studied stands.

Model fitting and statistical analysis

Linear and nonlinear regression analyses were used to model the *BCEFs* against the studied stand variables and the thinning characteristics. Derived variables, as well as interactions between variables, were also considered in the data analysis procedures. Multicolinearity was avoided by not allowing, in the same model regressors, variables with linear dependencies. The detection of undesirable dependencies was based

Table 2. Characterization of stand variables of the time series dataset (105 obs.)

Variable	Minimum	Maximum	Mean	SD
t (years)	15.0	69.0	46.9	10.3
N (trees ha^{-1})	200	1960	621	337
G (m^2 ha^{-1})	11.4	55.5	33.7	9.0
dg (cm)	9.7	43.6	28.1	6.6
hd (m)	7.1	27.2	18.3	3.9
SI (m)	11.5	22.1	16.0	1.9
V (m^3 ha^{-1})	41.1	634.5	291.9	111.1
B_{crown} (Mg ha^{-1})	8.8	50.7	29.8	8.4
B_{stem} (Mg ha^{-1})	17.5	214.6	107.7	39.7
B_{ABVG} (Mg ha^{-1})	26.3	262.0	137.5	47.8
B_{roots} (Mg ha^{-1})	6.3	16.6	10.8	2.4
B_{Total} (Mg ha^{-1})	34.5	275.2	148.3	49.1
$BCEF_{\text{ABVG}}$ (Mg m^{-3})	0.37	0.64	0.48	0.06
$BCEF_{\text{Total}}$ (Mg m^{-3})	0.39	0.84	0.53	0.08

t: Stand age. *N:* number of stems per hectare. *G:* basal area. *dg:* quadratic mean diameter. *hd:* dominant height. *SI:* site index at 35 yr reference age. *V:* stem volume. *B:* biomass. *BCEF:* Biomass Conversion and Expansion Factor. AVBG refers to aboveground and Total refers to above and belowground biomass. SD refers to standard deviation.

Table 3. Characterization of the stand variables before and after thinning for the thinning dataset

Variable	Minimum		Maximum		Mean		SD	
	Before Thin.	After Thin.	Before Thin.	After Thin.	Before Thin.	After Thin.	Before Thin.	After Thin.
t (years)	18	18	52	52	38.17	38.17	7.28	7.28
N (trees ha^{-1})	280	220	4,060	3,260	1,229.13	913.00	838.44	608.81
G (m2 ha^{-1})	14.51	10.73	58.35	51.59	32.86	27.98	8.90	7.88
dg (cm)	10.34	11.29	33.87	36.64	20.71	21.79	5.26	5.09
hd (m)	10.50	10.50	23.02	23.02	15.27	15.27	2.77	2.77
SI (m)	9.70	9.70	19.49	19.49	14.84	14.84	2.47	2.47
V (m^3 ha^{-1})	102.11	74.41	477.28	435.41	236.16	200.82	89.17	75.75
Bcrown (Mg ha^{-1})	12.64	93.30	49.34	43.92	27.92	23.88	7.6	6.77
Bstem (Mg ha^{-1})	39.9	30.43	148.36	138.55	84.95	73.91	26.17	23.70
BABVG (Mg ha^{-1})	54.74	39.73	195.79	178.03	112.86	97.78	33.20	30.06
Broots (Mg ha^{-1})	4.96	3.76	24.53	21.20	13.56	11.13	4.69	3.83
BTotal (Mg ha-1)	59.70	43.48	220.32	198.35	126.43	108.92	35.59	32.19
$BCEF_{ABVG}$ (Mg m^{-3})	0.39	0.41	0.59	0.60	0.49	0.50	0.05	0.05
$BCEF_{Total}$ (Mg m^{-3})	0.43	0.43	0.66	0.68	0.55	0.56	0.06	0.06

For symbol definitions, please see Table 1.

on the coefficient of determination of the regression when X_i is regressed against the other explanatory variables (R_i^2). The cut-off point of R_i^2 was set equal to 0.8, which corresponds to maintain the variance inflation actors, lower than 5 (Myers, 1990 and Neter *et al*., 1996). Candidate models were developed and residual analysis was carried out to examine the model appropriateness for the assumptions of the error term.

The normality of the residuals of the models was analysed through the Shapiro-Wilk (Shapiro and Wilk, 1965) test. Whenever the Shapiro-Wilk test was indicative of departure of normality and the visual analysis pointed out to an increasing variance pattern of the residuals, the Goldfeld-Quandt test for homocedasticity (Goldfeld & Quandt, 1965) was applied. In case of corroboration of heteroscedasticity, weighed regression analysis was performed.

The selection of the final model, from candidate models, was based on logical criteria and on the summary statistics of fit criteria, such as the coefficient of determination (R^2) and the root mean square error ($RMSE$). For the nonlinear models, a statistic R^2-like was used as a fit index. A 5% significance level was used throughout, unless stated otherwise. Statistical analyses were made with and JMP 9.0® software.

Table 4. Summary statistics of thinning key criteria (46 obs.)

Thinning criteria	Minimum	Mean	Median	Maximum	SD
Severity					
$N_{removed}$ (tree ha^{-1})	40	316	160	1,480	366
$G_{removed}$ (m^2 ha^{-1})	0.103	4.886	3.650	24.789	4.379
$P_N = N_{removed}/N_{before}$	0.063	0.226	0.182	0.649	0.149
$PG = G_{removed}/G_{before}$	0.003	0.145	0.113	0.445	0.107
Kind					
$R = dg_{removed}/dg_{before}$	0.216	0.770	0.775	1.103	0.173

N: number of stems per hectare. *G:* basal area. *dg:* quadratic mean diameter. The Index removed refers to the removed stand and before refers to the stand before thinning. P_N: proportion of trees removed. P_G : proportion of basal area removed, with *P* being a fraction of unity. *R*: ratio between the quadratic mean diameter of the thinned stand and the quadratic mean diameter of the stand before thinning. SD refers to standard deviation.

Results

Average values of $BCEF_{ABVG} = 0.48$ and $BCEF_{Total} = 0.53$ were found for the 105 sample plots (Table 2). According to the dispersion measures obtained for the conversion and expansion factors, it is confirmed that it is not appropriate to use an average value of *BCEF* for maritime pine. This applies to any of the compartments in the analysis. A slight increase of the factors following a thinning practice is noticeable, for aboveground component and whole tree (Table 3).

Changes in BCEFs with stands characteristics and across time and development of prediction models

A correlation analysis was performed to investigate the relationship between the *BCEFs* and the stand variables using the 105 observations of the time series data. The strongest linear association was found with *hd, SI*, *V* and *t* ($|r| > 0.5$), all in opposite trend. The variable selected as main regressor, for both the aboveground and total *BCEFs* models, was the dominant height. This variable combines simultaneously two parameters of population: age and site index, hence it is an interesting variable to describe the variation of the *BCEFs* while avoiding problems of multicolinearity.

Residual analysis of the fitted models allowed identifying quadratic mean diameter as a supplementary variable to be included in the model.

Scatterplots for the $BCEF_i$ against the explanatory variables *hd* and *dg* are shown in Fig. 1. The allometric model in the form $BCEF = a\ hd^b\ dg^c$, where *a*, *b* and *c* are the model parameters, was chosen as an appropriate functional form to model the relationships (Table 5). The estimation of the nonlinear models was made by applying the Gauss-Newton method at the nonlinear platform, of the JMP software. Analyses of the models were performed as described. In Table 5, Model 1 refers to the estimation of *BCEF* for the aboveground component, whereas Model 2 refers to the estimation of *BCEF* for the aboveground and roots (total) components.

The analysis of the residuals of the fitted models over the estimates of the *BCEFs* revealed a pattern of increasing variance. The presence of heteroscedasticity was corroborated by the Goldfeld-Quandt test at a significance level of 0.05. This type of heteroscedasticity was modeled as a power function of dominant height, that is $\sigma_i^2 = \sigma^2 X^k$, where *X* is *hd*. Estimation of *k* and fitting of the models using the weight functions

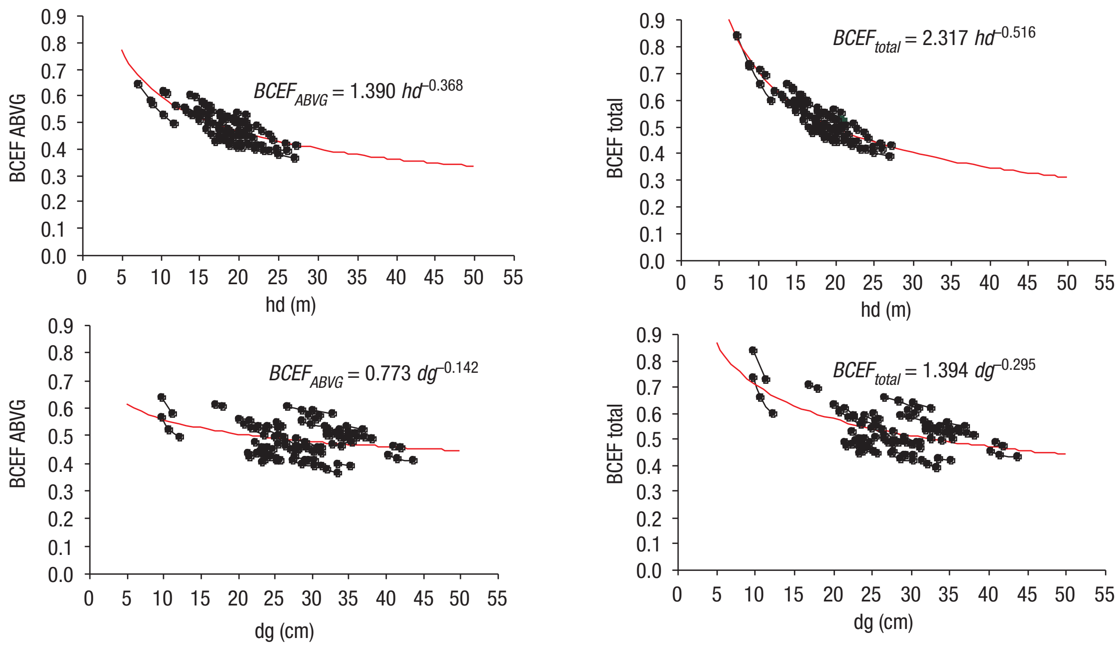

Figure 1. Measured Biomass Conversion and Expansion Factors (*BCEF*s) for the aboveground (ABVG) and Total compartments *versus* stand dominant height (*hd*) and quadratic mean diameter (*dg*). (● plot value – time series data set). Line: fitted allometric equation in the model form $BCEF = a\ X^b$, where *X* is *hd* or *dg*.

Table 5. Parameters of the allometric models for *BCEF*s established using the time series data without thinning

Mathematical model	Compartment	Model	a	b	c	R^2	RMSE
$BCEF = a\ hd^b\ dg^c$	ABVG	1	1.179 (0.041)	–0.890 (0.020)	0.505 (0.017)	0.955	1.8×10^{-2}
	Total	2	1.824 (0.078)	–0.909 (0.020)	0.414 (0.018)	0.945	1.3×10^{-2}

BCEF: Biomass Conversion and Expansion Factor (Mg m^{-3}). *hd:* dominant height (m). *dg:* quadratic mean diameter (cm). ABVG: aboveground. Total: aboveground and roots. The weighting function was $1/hd^k$ with $k = -0.919$ for the ABVG and $k = -2.807$ for total.

were according to the procedure proposed by Parresol (1999). The parameters (and the standard errors) of the nonlinear regression models estimated by the weighted least squares regression method are shown in Table 5. Analysis of the residuals for the fitted models (done graphically and by the Goldfeld-Quandt test) confirmed the presence of a constant error variance. Also shown in Table 5 are the goodness of fit statistics coefficient of determination and root mean square error for the proposed models.

According to the Shapiro-Wilk test results, the residuals of Model 1 follow a normal distribution (test statistic of 0.970, p-value = 0.137). Regarding Model 2, the test pointed towards a departure from normality (test statistic of 0.854; p-value < 0.0001). Visual analysis of the data (Fig. 1) and of the quantil-quantil plot (QQ) for the residuals were used to investigate the departure from normality. The QQ plot (graph not shown here) exposed a symmetrical distribution of the residuals, but with a heavy tail. The observations responsible for the results refer to the younger stands with lowest values of dominant height (*hd*) and quadratic mean diameter (*dg*). The observations are clearly visible at the left side of the graphs plotted in Fig. 1. This deviation from normality does not affect the estimates of the parameters, which remain unbiased and consistent, thus it has no direct implications in the quality of the estimations. Hence, a further correction was deemed unnecessary.

Thinning practice effects in the BCEFs and development of prediction models

A stepwise regression analysis and the "all possible models" analysis was performed as exploratory methods to investigate for the influence of stand characteristics and for the thinning variables descriptors on the variation of the *BCEF*s values. The response variable was defined as the ratio between the value of the *BCEF* after thinning and its counterpart before thinning. The tested regressors for the stand characteristics were: stand age, number of trees per hectare, basal area, quadratic mean diameter, dominant height, site index. The thinning descriptors tested were the number and basal area of trees removed ($N_{removed}$ and $G_{removed}$, respectively), the proportion of trees removed (P_N), the proportion of basal area removed (P_G), the ratio between the quadratic mean diameter of the thinned stand and the quadratic mean diameter of the stand before thinning ($dg_{removed}/dg_{before}$) and the ratio between the quadratic mean diameter of the stand after thinning and the quadratic mean diameter of the stand before thinning (dg_{after}/dg_{before}).

From the set of the variables tested, the ratio dg_{after}/dg_{before} presented a significant association (r > 0.7) with the variation of the *BCEFs* values for both compartments. For $BCEF_{Total}$, a high correlation value was also found with $N_{removed}$ (r = 0.772) and P_N (r = 0.734). Tentative models were developed for the aboveground compartment and for the total. Table 6

Table 6. Parameters of the allometric models for the ratio of *BCEF*s using the thinning dataset

Mathematical model	Compartment	Model	a	b	c	R^2	RMSE
$BCEF_{after}/BCEF_{before} = a\ hd^b\ (dg_{after}/dg_{before})^c$	ABVG	3	0.948 (0.023)	0.019 (0.009)	0.321 (0.027)	0.765	1.1×10^{-2}
$BCEF_{after}/BCEF_{before} = a\ P_N{}^b$	Total	4	1.037 (0.005)	0.015 (0.003)	—	0.433	1.2×10^{-2}

BCEF: Biomass Conversion and Expansion Factor. The sub indexes *after* and *before* refer to after thinning and before thinning, respectively. *hd:* dominant height (m). *dg*: quadratic mean diameter (cm). P_N: proportion of trees removed, with *P* being a fraction of unity. ABVG: aboveground, Total: aboveground and roots.

presents the estimation results for the selected models, concerning the estimates of the parameters (standard errors) and the fit statistics. All coefficients are statistically significant.

The residual analysis has shown no problems concerning heteroscedasticity. According to the Shapiro-Wilk test results, the residuals are normally distributed (test value of 0.956, with p-value = 0.131 for Model 3; test value of 0.948, with p-value = 0.064 for Model 4).

Discussion

Models for estimation of BCEFs

The study showed that it is not appropriate to use average values of *BCEF* for obtaining biomass estimates for maritime pine, hence, neither is any constant value, regardless of the compartment under consideration (aboveground or total). Fig. 1 shows a great variation in *BCEF* values with the quadratic mean diameter and with the dominant height. *BCEF*s values also vary with age, quality of the location and stand volume. The decrease in the *BCEF*s with volume was reported by Brown (1997). The decrease in the *BCEFs* with tree size and age as the stands develops, tending to a constant value as the stands get older, are also in agreement with the findings reported by other authors (Lehtonen *et al.*, 2004; Somogyi *et al.*, 2006; Tobin & Nieuwenhuis, 2007; Faias, 2009; González-García *et al.*, 2013).

Older stands and/or stands located in better sites tend to present lower values of factors. The decreases of *BCEFs* with respect to increasing values of dominant height were reported by other authors (Castedo-Dorado *et al.*, 2012; Sanquetta *et al.*, 2011; Faias, 2009; González-García *et al.*, 2013). Sanquetta *et al.* (2011) and Faias (2009) also indicated a decreasing relationship between the conversion factors and biomass expansion and the tree diameter for stands of pine species.

The results can be analyzed based on the expectation of achieving lower output biomass values for the same quantity of stem volume in younger stands, comparatively to an opposite trend that is expected to occur in older stands.

Two factors can interact and explain the phenomenon: (1) pattern of biomass allocation in the tree components (stem, branches, needles and roots), depending on the stage of stand development and (2) the growth rate. Sanquetta *et al*. (2011) explain this asymptotic decreasing behaviour due to the stabilization of growth rate and tree maturation. The authors provide full details for the explanation of this trend. The reported pattern is also attributed to the existence of distinct allometric coefficients along the developmental stage of stands with a higher relative allocation of biomass to the trunk component, as it progresses towards maturity. Results presented by Porté *et al.* (2002), regarding the distribution of the total biomass by components for maritime pine stands of different ages, confirm this trend. According to the authors, the percentage of branches' biomass relatively to the total biomass decreases significantly with age. In the study, the authors reported values of 49.3% at 5 years, compared to values of 13.2 and 11.4%, respectively, for stands of 26 and 32 years. Once the dominant height is a variable that simultaneously combines the age and quality of the station, it is expected that the dominant height indicator is even more relevant with *BCEFs* than age.

Evaluation of the influence of thinning on the values of BCEFs

The separation of the maritime pine data in two subsets, according to the occurrence or not of thinning during a minimum of a 5-year period, allowed investigating whether or not this management practice produced an evident effect on the *BCEFs* variation. Results from the regression analysis pointed out that the application of *BCEF* factors to estimate forest biomass in stands subjected to thinning should explicitly account for the effect of thinning. Although this effect is expected to reduce as stand growths after thinning, during a period of non disturbance, better estimates of biomass can be obtained when thinning is accounted for. In general terms, the *BCEF* model for the aboveground compartment discloses a tendency to increase with dominant height. As this variable can be interpreted as a surrogate of age and site quality, greater variations are predicted for better sites and/or along stand development. The effect of the stage of stand development and the site quality was analyzed. Regarding the ratio of the diameters, characterizing the type of thinning, there is also a positive trend. With regard to the *BCEF* variable for the above and belowground components ($BCEF_{Total}$), there will be an increase of the values with an increasing proportion of trees removed, that is, with the severity of the thinning. Results are in accordance to the expected effects of a low to moderate selective thinning in stand growth after thinning. A short-term positive effect of thinning on tree growth, due to the increase of available space for growth, is well reported for the species (*e.g.* Luis & Guerra, 1999; Fonseca, 2004).

The proposed models estimate changes in the *BCEFs* after a thinning, depending on stand characteristics and on the thinning severity and type. The models (3) and (4) should be used in the 1-5 years period after the thinning is performed. After 5-years of non disturbance, models (1) and (2) can be securely applied.

Conclusions

For periods of undisturbed growth, the *BCEF* values vary with stand age and with the quality of the station. These effects are accounted for into a surrogate variable, which is the stand dominant height. For a fixed value of the dominant height, variations of the *BCEFs* values are still observed. Results have shown that the differences are partially explained by the mean size of the trees, described by the quadratic mean diameter, which is influenced by stand development and density. For increasing values of dominant height and of quadratic mean diameter, higher values of stand biomass are expected to occur.

The maritime pine stands are subjected to light thinning from below to moderate thinning. When thinning occurs, the thinning practice has proved to have an obvious effect in the variation of the *BCEF*s. With regard to the aboveground compartment, for a fixed value of dominant height, thinning type and thinning severity influence the variation of *BCEF* value. The effect is built-in the surrogate variable quadratic mean diameter ratio (dg_{after}/dg_{before}). The expected *BCEF* variation increases also with increasing values of the stand dominant height. The variables which affect the variation of *BCEF* for the total compartments refer to the severity of thinning, expressed in number of trees (P_N).

The proposed *BCEF*s equations are simple but effective models that allow predicting the biomass of a stand from easier-to obtain stand characteristics such as dominant height and quadratic mean diameter. These variables are currently recorded in inventories. If a thinning is performed, the ratio models provide information of the expected change in the *BCEF*s, depending on the severity and type of the thinning. Furthermore, the system of equations presented in this work easily conjugate with existing growth and yield models that solely provide information on stem volume, enlarging their outputs to biomass predictions. These prediction models should produce helpful biomass information to support maritime pine management decisions for commercial uses (timber, energy supply and fiber) and environmental goods.

Acknowledgements

The authors would like to thank the commitment of Professor Carlos Pacheco Marques to obtain funding to support the installation and monitoring of permanent plots in the Valley Tâmega's maritime pine (under PAMAF Project 4004 and Project Agro 372) which supported the database DataPinaster used in this study.

References

Baldwin VC, Peterson Jr KD, Clark III A, Ferguson RB, Strub MR, Bower DR, 2000. The effects of spacing and thinning on stand and tree characteristics of 38-year-old Loblolly Pine. For Ecol Manage 137: 91-102.

Brown S, 1997. Estimating biomass and biomass change of tropical forests: a Primer. FAO Forestry Paper. No. 134.

Brown S, 2002. Measuring carbon in forests: current status and future challenges. Environmental Pollution 116: 363-372.

Castedo-Dorado F, Gómez-García E, Diéguez-Aranda U, Barrio-Anta M, Crescente-Campo F, 2012. Aboveground stand-level biomass estimation: a comparison of two methods for major forest species in northwest Spain. Ann For Sci 69: 735-746.

Eriksson E, 2006. Thinning operations and their impact on biomass production in stands of Norway spruce and Scots pine. Biomass and Bioenergy 30: 848-854.

Faias SMMP, 2009. Analysis of biomass expansion factors for the most important tree species in Portugal. M Sc thesis. Instituto Superior de Agronomia, Lisboa, Portugal.

Fonseca TF, 2004. Modelação do crescimento, mortalidade e distribuição de diâmetro para povoamentos de pinheiro bravo no Vale do Tâmega. Ph D thesis. Universidade de Trás-os-Montes e Alto Douro,Vila Real, Portugal.

Fonte CMM, 2000. Estimação de volume total e mercantil em *Pinus pinaster* Ait. no Vale do Tâmega. Engenering Final Report. Universidade de Trás-os-Montes e Alto Douro, Vila Real, Portugal.

Goldfeld SM, Quandt RE, 1965. Some tests for homoscedasticity. Journal of the American Statistical Association 60: 539-547.

González-García M, Hevia A, Majada J, Barrio-Anta M, 2013. Above-ground biomass estimation at tree and stand level for short rotation plantations of *Eucalyptus nitens* (Deane & Maiden) Maiden in Northwest Spain. Biomass and Bioenergy 54: 147-157.

Hasenauer H, Burkhart HE, Amateis RL, 1997. Basal area development in thinned and unthinned loblolly pine plantations. Can J For Res 27: 265-271.

IPPC, 2006. Generic methodologies applicable to multiple land-use categories, Chapter 2. In: Guidelines for national greenhouse gas inventories. Agriculture, forestry and other land use, Vol 4 pp: 2.1-2.59.

Johnson WC, Sharpe DM, 1983. The ratio of total to merchantable forest biomass and its application to the global carbon budget. Can J For Res 13: 372-383.

Ketterings QM, Coe R, Noordwijk M, Ambagau Y, Palm CA, 2001. Reducing uncertainty in the use of allometric biomass equations for predicting above-ground tree biomass in mixed secondary forests. For Ecol Manage 146: 199-209.

Lehtonen A, Mäkipää R, Muukkonen P, 2004. Biomass expansion factors (BEFs) for Scots pine, Norway spruce and birch according to stand age for boreal forests. For Ecol Manage 188: 211-224.

Longuetaud F, Santenoise P, Mothe F, Kiessé TS, Rivoire M, Saint-André L, Ognouabi N, Deleuze C, 2013. Modeling volume expansion factors for temperate tree species in France. For Ecol Manage 292: 111-121.

Lopes DMM, 2005. Estimating net primary production in *Eucalyptus globulus* and *Pinus pinaster* ecosystems in Portugal. Ph D thesis. Kingston University, Kingston, UK.

Luis JS, Fonseca TF, 2004. The allometric model in the stand density management of *Pinus pinaster* in Portugal. Ann For Sci 61: 807-814.

Luis JS, Guerra HP, 1999. Influence of alternative thinning regimes on *Pinus pinaster* Ait. stand dynamics in northern Portugal. Silva Lusitana 7: 11-21.

Marques CP, 1991. Evaluating site quality of even-aged maritime pine stands in northern Portugal using direct and indirect methods. For Ecol Manage 41: 193-204

Myers RH, 1990. Classical and modern regression with applications, 2nd ed. PWS Publishers, USA. 488 pp.

Neter J, Kutner MH, Nachtsheim CJ, Wasserman W, 1996. Applied linear regression models, 3rd ed. IRWIN, USA.720 pp.

Nunes L, Lopes D, Rego FC, Stith TG, 2013. Aboveground biomass and net primary production of pine, oak and mixed pine-oak forests on the Vila Real district, Portugal. For Ecol Manage 305: 38-47.

Oliveira AC, Pereira JS, Correia AV, 2000. A silvicultura do pinheiro bravo. Centro Pinus, Porto, Portugal.

Pardé J, 1980. Forest biomass. Forestry Abstracts 41: 343-362.

Parresol BR, 1999. Assessing tree and stand biomass: a review with examples and critical comparisons. For Sci 45: 573-593.

Parresol BR, 2002. Biomass. In: Encyclopedia of environmetrics (El-Shaarawi Abdel H, Piegorsch, Walter W). John Wiley & Sons, Ltd Chichester, UK. pp: 196-198.

Páscoa F, Martins F, Salas R, João C, 2004. Estabelecimento simultâneo de equações de biomassa para Pinheiro bravo. In: II Simpósio Iberoamericano sobre Gestión y Economia Forestal, Barcelona, Spain. pp: 18-20.

Picard N, Saint-André L, Henry M, 2012. Manual for building tree volume and biomass allometric equations: from field measurement to prediction. Food and Agricultural Organization of the United Nations, Rome, and Centre de Coopération Internationale en Recherche Agronomique pour le Développement, Montpellier. France. 215 pp.

Porté A, Trichet P, Bert D, Loustau D, 2002. Allometric relationship for branch and tree woody biomass of Maritime pine (*Pinus pinaster* Ait.). For Ecol Manage 158: 71-83.

Ruiz-Peinado R, Bravo-Oviedo A, López-Senespleda E, Montero G, Río M, 2013. Do thinnings influence biomass and soil carbon stocks in Mediterranean maritime pinewoods? Eur J For Res 132: 253-262.

Sanquetta CR, Corte APD, Silva F, 2011. Biomass expansion factor and root-to-shoot ratio for Pinus in Brazil. Carbon Balance Manag 6: 6.

Shapiro SS, Wilk MB, 1965. An analysis of variance test for normality (complete samples). Biometrika 52: 591-611.

Soares P, Tomé M, 2012. Biomass expansion factors for *Eucalyptus globulus* stands in Portugal. For Syst 21: 141-152.

Somogyi Z, Cienciala E, Mäkipää R, Muukkonen P, Lehtonen A, Weiss P, 2006. Indirect methods of large-scale forest biomass estimation. Eur J For Res 126: 197-207.

Telmo C, Lousada J, 2011. Heating values of wood pellets from different species. Biomass and Bioenergy 35: 2634-2639.

Tobin J, Nieuwenhuis M, 2007. Biomass expansion factors for Sitka spruce (picea sitchensis (Bong.) (Carr.) in Irland. Eur J For Res 126: 189-196.

Viana H, Vega-Nieva DJ, Ortiz-Torres L, Lousada J, Aranha J, 2012. Fuel characterization and biomass combustion properties of selected native woody shrub species from central Portugal and NW Spain. Fuel 102: 737-745.